Enhancing Resilience in Residential Buildings: Assessing Comfort under Blackout Scenarios with a Modular Multi-Zone White-Box Modeling Approach

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Abstract

Residential buildings are increasingly required to maintain suitable indoor conditions under both occupant-related activities and external disruptions such as blackouts. However, simplified building representations often fail to capture room-level thermodynamics, occupant behaviors, and their interactions with building energy systems in a unified and physically interpretable manner. This paper proposes a modular multi-zone white-box modeling approach for residential buildings that couples room-level building physics with configurable energy system components via a Python-to-Modelica workflow and explicitly incorporates occupant-related disturbances as model inputs. Its feasibility is demonstrated through a simplified three-zone residential case study under blackout conditions, comparing passive, buffer-supported, and PV/BESS/HP-supported configurations, highlighting the potential of the model as a flexible basis for occupant-aware comfort and resilience analysis in residential buildings.

CCS Concepts

• **Computing methodologies → Modeling methodologies**.

Keywords

Building, Resilience, Multi-zone, White-box, Modeling, Comfort, Blackout

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1 Introduction

To ensure optimal comfort in residential buildings while maintaining high energy efficiency, these buildings are expected not only to provide comfortable indoor conditions during normal operation but also to maintain acceptable living conditions during disturbance events such as power outages [23]. In blackout scenarios, indoor comfort can drop rapidly [10], especially in winter, and the thermal response is often not spatially uniform across rooms. Factors such as facade orientation, envelope exposure, internal connections, and occupant actions can lead to significant temperature differences between thermal zones [9]. Simultaneously, modern residential buildings may have multiple competing energy demands, including space heating, ventilation, and electricity for household appliances. Under outage conditions, where available on-site energy resources are limited [14], the question is therefore not only whether comfort can be maintained, but also how thermal and electrical demands should be balanced in a resilience-oriented manner.

Recent studies have increasingly focused on building thermal resilience under disturbance conditions, moving beyond static comfort assessments toward dynamic analyses of extreme events such as blackouts [8]. Previous studies have shown the importance of evaluating resilience-oriented building performance during energy supply disruptions [15] and highlighted the role of system support in mitigating discomfort [1]. However, current approaches still have limitations when the objective is to analyze blackout resilience in a room-resolved, occupant-aware, and physically interpretable way.

Non-heterogeneous model. Many existing methods rely on single-zone or other simplified reduced-order representations. Early works—for example, TEASER [20] used by Modelica AixLib, and CityBES [4]—already recognized that such models often fail to capture spatially heterogeneous thermal responses across rooms, including inter-room coupling and the propagation of local disturbances. This limitation is particularly critical for blackout assessment [11][19], as thermal discomfort within a residence can be unevenly distributed, and the overall condition of the indoor environment may mask the vulnerability of specific rooms [12].

Inflexible model configuration. Models that are configured for one specific operating condition or disturbance scenario are difficult to generalize to other situations [25]. Saini et al. [21] explored the relationship between building resilience and energy efficiency rating under power outages in extremely cold weather by using IDA ICE simulation [6]. In practice, however, resilience assessment often requires systematic comparison across different combinations of occupant disturbances, building envelope conditions, and backup energy system configurations. A model developed for a specific scenario, such as normal operation or heat-wave analysis, may not be directly applicable to outage studies involving different thermal support strategies or limited backup power resources [22].

Neglect of occupant-related actions. Occupant behaviors are often underestimated, although they can strongly affect both indoor

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thermal conditions and the use of limited backup energy during outages [2]. Actions such as ventilation and using appliances are not merely secondary effects; they can directly alter heat losses, internal gains, and the competition between thermal and electrical services [13][18]. However, these effects are often addressed only implicitly, limiting the interpretability of resilience assessments in residential contexts. After comparing 274 academic papers, Siu et al. [23] recommended that residents' adaptive behaviors be formally incorporated into resilience analysis, norms, and standards.

Contributions. Addressing these challenges, blackout-oriented resilience assessment in residential buildings requires a modeling framework that simultaneously preserves room-level thermal heterogeneity, supports flexible reconfiguration across disturbance and system scenarios, and explicitly represents occupant-related actions. In particular, we

- introduce a modular multi-zone white-box modeling approach that links room-level physics with configurable energy system components in a unified Python-to-Modelica workflow;
- incorporate occupant-related disturbances, such as ventilation events and appliance electricity demand, as explicit and configurable inputs to the building energy model;
- enable systematic comparison of blackout scenarios with different thermal and electrical support setups, facilitating occupant-aware resilience assessment under limited on-site energy availability.

The remainder of this paper is structured as follows: Section 2 presents the modeling methodology and the simulation setup. Section 3 evaluates the proposed approach through a comparative blackout case study. Section 4 discusses the implications, limitations, and concludes with potential future extensions of the work.

2 Methodology

Based on the modular and transferable white-box modeling approach used in this study, various energy system components and building envelope models, as well as occupant-related behavioral agents, are integrated. Furthermore, power outage scenarios are taken as an example for evaluating system response.

2.1 Building Modeling Approach

The modeling approach adopted in this study is based on RoomFlex6D [5], a novel Python-based modular multi-zone white-box modeling tool designed for rapid, topology-driven model generation. Unlike general semantic building standards such as CityGML [16], IFC [3], or gbXML[7], which require detailed thermal models for each specific element, RoomFlex6D provides a structured representation of building zones and their adjacency relationships, and allows hydronic heating-related elements and their coupling to specific zones to be configured in a modular manner, enabling the automatic generation of simulation-ready building models under different zoning and system configurations.

The tool provides a Lego®-like zone-based model representation for buildings. Each room is described as a set of connected thermal zones, and each zone is defined by six directional faces (N/E/S/W/U/D). For every face, an adjacency boundary type is assigned to indicate whether the surface is connected to ambient conditions, neighboring zones, windows, doors, or ground. Based on the topological description, RoomFlex6D automatically generates parameter tables for Modelica model construction, supporting physically interpretable white-box simulation of building thermal behavior, which includes

- conductive transfer from walls, floors, and roofs,
- convective exchange between zoned air and interior surfaces,
- convective exchange on exterior surfaces affected by external temperature and wind speed,
- solar radiation through transparent components, and the heating of the external surface by solar radiation,
- internal heat generated by people and equipment, and
- heat loss due to infiltration and ventilation.

2.2 3-zone Case

To demonstrate building behaviors during a blackout in a transparent yet physically meaningful manner, a simplified three-zone residential case generated by RoomFlex6D is used as the evaluation testbed, which is shown in Figure 1, preserving thermal coupling, varying exposure conditions, and localized occupant disturbances, while remaining compact enough to enable interpretable comparisons across multiple configurations and disruption scenarios. Meanwhile, the envelope material properties are derived from the Living Lab buildings [26] at Karlsruhe Institute of Technology (KIT) Campus North, ensuring the physical basis of the simplified case study.

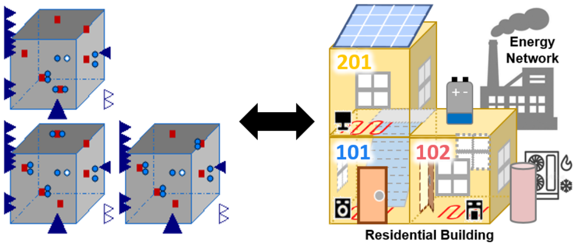

Figure 1: Python-to-Modelica via RoomFlex6D: a 3-zone Modelica model instance generated from the RoomFlex6D (left) and its schematic graph representation (right).

The case study model consists of three rooms, denoted as 101, 102, and 201. Rooms 101 and 102 are located on the lower floor, while Room 201 is positioned above Room 101 on the upper floor, as illustrated in Figure 1. Room 101 is thermally coupled to Room 102 through an internal door, whereas Rooms 101 and 201 are connected via the staircase opening. The three rooms are therefore intentionally assigned different boundary characteristics.

2.3 Simulation Setup

A unified simulation setup is defined to compare building energy performance under varying operating and disturbance conditions.

Weather data and setpoints. The main simulations cover a three-day winter period using weather data from Karlsruhe, Germany, in the year 2025, including outdoor temperature and solar radiation. Indoor temperature starts at 21°C, with setpoints of 21°C for Rooms 101 and 102 and 23°C for Room 201.

Behavioral inputs. Two forms of the occupant-related effects are considered in this study. First, a periodic ventilation event is applied to Room 102. Second, appliance electricity demand is represented using profiles generated with LoadProfileGenerator (LPG) [17], covering typical residential end uses distributed across the three rooms, including washing and kitchen appliances in Rooms 101 and 102, respectively, and entertainment loads in Room 201. In addition, the internal door between Rooms 101 and 102 is modeled as 80% open, allowing local disturbances to propagate across zones.

Blackout event. As an example disturbance case, this study assumes an electricity blackout event that interrupts the external electrical supply for the entire second day of the simulation.

Scenarios setup. Based on this setup, four scenarios are compared, including the envelope-only baseline (S0), a ventilation-only case (S1), a thermal buffer-supported case (S2), and a Photovoltaic (PV)-Battery Energy Storage System (BESS)-supported case (S3), as described in Table 1 and Figure 2. It is worth noting that the blackout is not treated as the only intended application of the modeling approach, but rather as a representative disturbance to demonstrate the model's capabilities in resilience-oriented analysis.

Table 1: Scenario matrix of the evaluated configurations.

Scenario	Ventilation	Buffer	PV	BESS	HP	Appl.
S0 (Base)						
S1	x					
S2	x	x				
S3	x		x	x	x	x

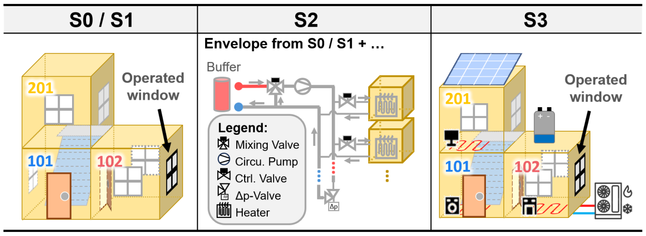

Figure 2: Schematic building representations of all presented scenarios with modularity configurations.

3 Evaluation

This section evaluates the proposed Python–to-Modelica modeling approach through a systematic comparison of residential building behavior. Starting from a baseline case without active equipment, and then progressively adding occupant disturbance, storage, generation, and heating-related components.

3.1 Scenario S0: Baseline

The baseline case serves as a passive reference in the presented paper, so that indoor thermal dynamics are determined solely by the envelope, outdoor weather, and solar gains.

As shown in Figure 3, indoor temperatures decrease over the three-day horizon, with only limited daytime recovery due to solar gains. Although all rooms follow a similar overall cooling trend, the model resolves distinct room-level responses: Rooms 102 warmed faster during the day, consistent with higher solar radiation and larger window-to-wall ratios, but also cooled faster at night. Room 101 shows a slightly more buffered temperature change. The door between Rooms 101 and 102 introduces inter-room coupling, but does not fully homogenize temperatures. This baseline thereby provides a physically interpretable reference for subsequent equipment-enabled resilience scenarios.

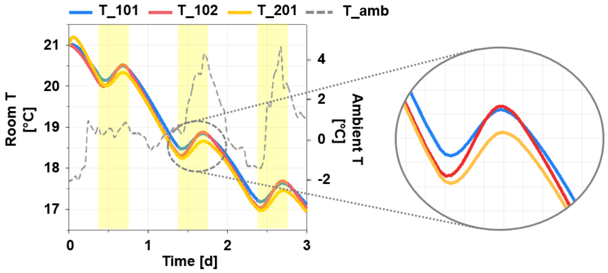

Figure 3: The changes of temperature in each room (left y-axis) and the much colder ambient temperature (right y-axis) of scenario S0. The yellow shadings represent the duration of sunlight.

3.2 Scenario S1: Periodic Ventilation

This scenario extends the passive baseline by introducing a periodic window-opening event in Room 102, where the window (as shown in Figure 2) opens 50% for 20 minutes at noon for ventilation [24], demonstrating how the framework represents occupant-related disturbances as explicit, configurable room-level inputs.

Figure 4 shows that the opening events (marked with black arrows) cause an immediate cooling response in Room 102, caused by increased heat exchange with the outdoor environment. The effect then propagates to Room 101 through the open door, while Room 201 is less affected. This indicates coupling between rooms and spatial attenuation of disturbances in a multi-zone building. After each ventilation period, Room 102 shows partial temperature recovery, which can be interpreted as the elimination of direct outdoor air exchange, after which the room temperature is primarily controlled by the building envelope dynamics and thermal interactions with adjacent spaces. Overall, this scenario shows that the proposed model can capture not only the local impact of occupant actions but also their timing, propagation paths, and decay across rooms, which is crucial for physically interpretable resilience assessments under power-outage conditions.

3.3 Scenario S2: Buffer-Supported Resilience under Blackout

To optimize the operation of heating units, residential buildings are often equipped with heat buffer tanks. This scenario considers the same periodic ventilation disturbance as in S1 but adds a buffer-supported Underfloor Heating (UFH) system, as shown in Figure 2.

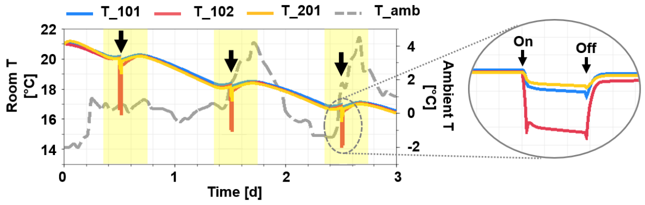

Figure 4: Results of three-day simulation of scenario S1 with a periodic ventilation event (On/Off) in Room 102.

During the blackout day, the heating loop remains in operation, with loop flow rate controlled by a room-temperature PI controller and the 3-way mixing valve regulated to maintain a supply temperature of 35 °C. The buffer is initialized at 50 °C.

In contrast to S1, Figure 5 shows that indoor temperatures remain largely within a comfortable range despite the repeated opening events. The additional heat loss from the ventilation is still evident, but its impact on room comfort is substantially reduced by the available buffer support. A further plausible control response is evident in the mixing-valve signal, which is elevated overall during opening periods, indicating an attempt to inject more heat into the UFH loop to compensate for the disturbance. It is shown that buffer-supported hydronic heating can significantly improve winter blackout resilience under the same occupant-related disturbance.

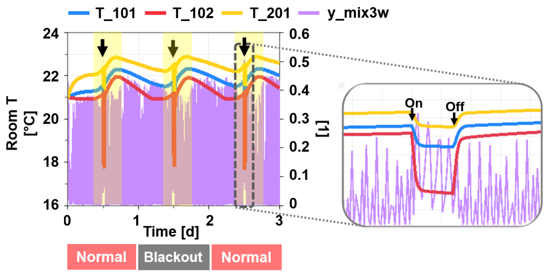

Figure 5: Results of three-day simulation of scenario S2, with the 3-way mixing valve state.

3.4 Scenario S3: System-Supported Resilience under Blackout

Scenario S3 removes the thermal buffer but activates PV with an off-grid inverter, BESS, Heat Pump (HP), and appliance electricity demand while retaining the same ventilation disturbance as in S1.

As shown in Figure 6, the PV-BESS-HP combination provides significant thermal support during the blackout period, as indoor temperatures remain at higher levels and decrease more slowly than in the S1 cases. Meanwhile, occupant-related disturbances remain relevant, and the heat pump's operation to combat cooling during window opening is also explicit in Figure 6. Because the BESS is charged only by the PV system and stops discharging at 5% State of Charge (SOC), resuming only after being recharged above 25%, thermal support is directly constrained by battery availability: the HP helps maintain indoor comfort but also draws on a finite battery reserve, causing the SOC to decrease substantially during the outage.

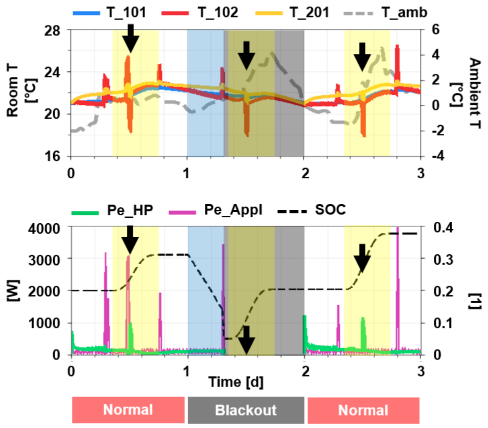

Figure 6: Results of three-day simulation of scenario S3, with the power consumption of HP and appliances, as well as SOC of BESS. The blue shadings represent the duration of battery active support, and the grey the duration of downtime.

In addition to heating indoor spaces, the demand from household appliances adds a second layer of competition for the limited power supply of the BESS. In the uncontrolled case presented in this paper, results show that appliance downtime is approximately 16.5 h, indicating that improved thermal resilience does not automatically translate into uninterrupted end-user operation. Thus, S3 highlights a key resilience trade-off between maintaining indoor comfort and supporting electrical end uses when using a backup energy source.

4 Discussion and Conclusion

This study addresses key limitations in current research on residential blackout resilience, helps bridge the gaps by combining room-level building physics, configurable energy system components, and explicit occupant actions within a unified Python-to-Modelica workflow. The results show that thermal resilience is spatially non-uniform across rooms, that occupant disturbances, such as ventilation and appliance use, can significantly influence indoor conditions and system behavior, and that blackout performance is best understood as a coupled electrothermal problem rather than a purely thermal or electrical one.

The evaluated scenarios further indicate that the benefits from the supportive systems remain constrained by limited storage and competition between heating and other electrical end uses. Consequently, residential design should emphasize electrothermal co-planning, rather than the isolated integration of single technologies. As the analyses show, significant investments are needed to achieve a certain level of resilience in buildings and, consequently, an increased comfort for their occupants. However, the present study is limited by a simplified occupant model and the lack of adaptive control. Future work will therefore build on the proposed framework to investigate occupant-aware control and predictive scheduling, with the aim of further improving indoor comfort and service continuity during outages.

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